Extreme ultraviolet interferometry: measuring and aligning an EUV four-mirror ring-field optical system

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INTRODUCTION

Extreme ultraviolet (EUV) lithography is a promising and viable candidate for circuit fabrication with critical dimensions from 100 nm down to 30 nm or smaller. Voted in 1998 by a group of semiconductor industry leaders as the most viable next-generation lithography candidate, EUV lithography research is conducted by a large-scale collaborative effort involving three national laboratories (Lawrence Berkeley, Lawrence Livermore, and Sandia National Laboratories, collectively called the *Virtual National Laboratory, or VNL*) and the EUV Limited Liability Corporation (EUV LLC), a consortium including Intel, Motorola, and Advanced Micro Devices. A number of other groups around the world are also involved in EUV lithography research, including both Japanese and European efforts.

Operating near 13-nm wavelength, optical systems for EUV lithography require multilayer-coated, all-reflective elements with a system numerical aperture of 0.1 or higher. In a region of the spectrum where all materials are highly absorptive, the mirrors utilize molybdenum/silicon multilayer coatings to achieve reflectivities near 70% at normal incidence. The suggested wavefront aberration tolerance for these sophisticated systems, composed of multiple aspherical elements, is only 0.27 nm, or one-fiftieth of an EUV wavelength [1]. This places extremely high demands on the fabrication of EUV mirror substrates and multilayer coatings, and even higher demands on the accuracy of metrology tools required to characterize them.

Within an EUV optical system, the EUV wavefront is determined by a combination of the geometric figure of the mirror surfaces and the properties of the multilayer coatings, which are deposited across mirror areas of several square inches. While advanced visible-light interferometric techniques possessing the required measurement accuracy are being developed [2], phase effects arising from multilayer coating defects and thickness errors are measurable only at the EUV operational wavelength. Final alignment and qualification may require *at-wavelength* testing, using EUV light to predict the imaging performance of an optical system. These factors motivate the development of high-accuracy EUV wavefront-measuring interferometry now in progress at the ALS.

A NOVEL EUV INTERFEROMETER DEVELOPED FOR HIGH-ACCURACY

Researchers from LBNL's Center for X-Ray Optics (CXRO) have built prototype EUV interferometers at ALS beamlines 12.0.1.2 and 12.0.1.3. By spatially-filtering undulator radiation, the interferometers takes advantage of the high brightness from the ALS to generate coherent EUV light. Where high-brightness EUV light is available, the phase-shifting point-diffraction interferometer (PS/PDI) [3,4,5] has emerged as the high-accuracy system measurement tool of choice. It now serves as the accuracy standard for all other EUV system metrologies, including visible-light interferometry and alternate EUV interferometry methods being pursued by the CXRO.

The PS/PDI is a common-path interferometer that incorporates pinhole diffraction to generate reference wavefronts of extraordinarily high spherical accuracy. A schematic of the optical

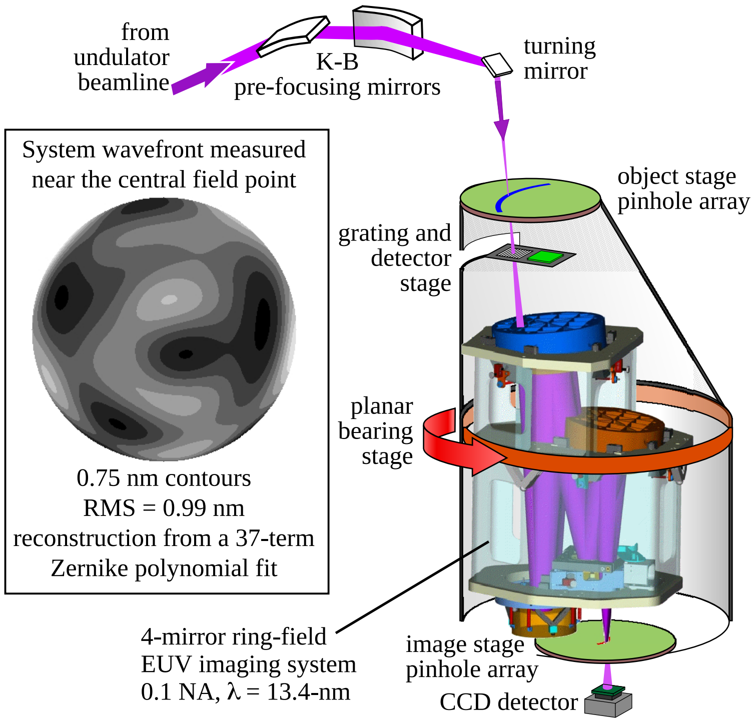

Figure 1. The extreme ultraviolet phase-shifting point diffraction interferometer (EUV PS/PDI) constructed at Beamline 12.0.1.3 for the measurement of a four-mirror ring-field EUV optical system called the Projection Optics Box., or PO Box. The interferometer spatially filters coherent EUV light from ALS to produce reference wavefronts of exceptionally-high spherical accuracy. System wavefront quality measurements are made across the large field of view. The data is used to align the four-mirror system, and to predict imaging performance.

design of the PS/PDI is shown in Fig. 1. Open-stencil pinholes smaller than 100-nm diameter are used to test the latest high-quality EUV optics. A coarse grating beam splitter placed before the test optic divides the beam into multiple diffractive orders that are brought to spatially separated foci in the image-plane. One beam, the *test* beam, containing the aberrations of the test optical system, is allowed to pass through a large window in an opaque mask placed in the image-plane. A second beam, the *reference* beam, is spatially filtered by a pinhole smaller than the diffraction-limited resolution of the test optic, and becomes the spherical reference wave. These two beams overlap to produce an interference fringe pattern that is detected by an EUV CCD detector. The interference pattern may be interpreted as a coherent comparison of the aberrated test beam with the nearly-perfect spherical reference beam; the fringe pattern thus reveals the aberrations in the test optic. Translation of the grating beam splitter is used to introduce a controlled relative phase-shift between the test and reference beams, allowing phase-shifting interferometry techniques to be employed.

Earlier efforts to characterize the accuracy of the EUV PS/PDI have verified the performance of the interferometer. [6] Experiments have since pushed rms wavefront uncertainty level to 0.4 Å rms (λ/330) using 80-nm diameter pinholes with 0.082 NA optical systems. Since the pinhole functions as a spatial filter for the aberrated test beam, it is expected that as higher quality-optics are tested, the reference wavefront quality can be further improved.

NEW OPTICS AND NEW MEASUREMENT CAPABILITIES

The focus of the interferometry research in 1999 was on the measurement of a new four-mirror ring-field EUV optical system, composed of three aspherical and one spherical element. [7] This new optic, called the Projection Optics Box (PO Box), represents the collaborative efforts of the three VNL laboratories, and our industry sponsors, requiring more than two years of development. During 1998-99, a new branchline (12.0.1.3) of beamline 12.0 was constructed specifically for EUV interferometric measurement of the PO Box. The branchline became operational late in 1999 and was used in a successful, iterative series of interferometric measurements and alignment. [8]

To complete a measurement series, the system wavefront must be measured at positions spanning the large, 26-mm-wide ring field of view in the image plane. To accomplish this, the entire optical system and accompanying interferometer rotate together as one unit on an annular, planar bearing stage, underneath a stationary, focused EUV beam. To access the entire field of view, the optic must be rotated by 30 degrees and translated over about 5 mm, all within a large vacuum chamber. Arrays of spatial-filter pinholes in the object and image planes define the measurement positions and their conjugates. Software was developed to guide the system from one pinhole position to the next, performing coordinate transformations and keeping track of the pinhole positions in real time.

In addition to the wavefront-measuring interferometry, the PS/PDI configuration is used for other at-wavelength metrologies. The interferometer has been used to measure system flare, resulting from mid-spatial frequency roughness in the mirror substrates. By varying the wavelength, chromatic wavefront aberrations related to the multilayer coatings, and the spatial variation of the transmitted peak-wavelength and bandwidth across the pupil have also be studied.

The PO Box is destined for use in an integrated exposure system, called the Engineering Test Stand (ETS) now being developed at Sandia National Laboratory in Livermore. [9]

REMARKS FOR FUTURE WORK

In 2000, beamline 12.0.1.3 will be used for interferometry of a second PO Box, fabricated to tighter tolerances than the first. Plans are being made to use the endstation with the second PO Box for small-field exposure experiments in advance of its use in the ETS.

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